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Production of neutral and doubly charged partners of $\mathbf{D_{s0}^{+}(2317)}$

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Production of the neutral and doubly charged partners $\hat{F}_I^0$ and $\hat{F}_I^{++}$ of $D_{s0}^+(2317)$ as the charm-strange four-quark meson $\hat{F}_I^+$ is studied in relation to observation of $D_{s0}^+(2317)$. It is argued that observation of $\hat{F}_I^{++}$, $\hat{F}_I^0$ and $\hat{F}_0^+$ in inclusive $e^+e^- \to c\bar{c}$ would be difficult, although $\hat{F}_I^{++}$ might be observed in $B_u^+ \to D_s^+\pi^+D^-$. Observations of $\hat{F}_I^0$ and $\hat{F}_0^+$ might be possible in hadronic B decays.

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Recently, the resonance $D_{s0}^+(2317)$, which decays into $D_s^+\pi^0$, has been observed in $e^+e^- \to c\bar{c}$ experiments [1, 2]. In addition, a resonance that is degenerate with it has been observed in B decays [3, 4]. While it is known that their spin-parity is $J^P = 0^+$ and their width is very narrow, their isospin quantum number has not yet been definitively determined. (A comprehensive review on new heavy mesons is given in Ref. [5].) To determine the isospin quantum number of $D_{s0}^+(2317)$, its decay properties have been studied [6] by assigning it to various scalar meson states: (i) the $I_3 = 0$ component $\hat{F}_I^+$ of iso-triplet four-quark mesons [7], $\hat{F}_I \sim [cn][\bar{s}\bar{n}]_{I=1}$ ($n = u,\, d$); (ii) the iso-singlet four-quark meson, $\hat{F}_0 \sim [cn][\bar{s}\bar{n}]_{I=0}$, which might not be identical to that considered in Ref. [8]; (iii) the conventional scalar $D_{s0}^{*+} \sim \{c\bar{s}\}$ meson [9]. The results obtained in these studies are (i) $R(\hat{F}_I^+) \simeq 0.005$, (ii) $R(\hat{F}_0^+) \simeq 7$ and (iii) $R(\hat{D}_{s0}^{*+}) \simeq 60$, where $R(S)$ is given by $R(S) = \Gamma(S \to D_s^{*+}\gamma)/\Gamma(S \to D_s^+\pi^0)$, with $S = \hat{F}_I^+,\, \hat{F}_0^+,\, D_{s0}^{*+}$. The same approach predicts [6] $R(D_s^{*+})^{-1} \simeq 0.06$ which reproduces well the measured ratio [10], $R(D_s^{*+})^{-1}_{\rm exp} = 0.062 \pm 0.006 \pm 0.005$, where $S = D_s^{*+}$, and thus the present approach seems to be sufficiently reliable. By comparing the above results with the experimental constraint [2]

$$R(D_{s0}^+(2317))_{\rm exp} < 0.059, \tag{1}$$

it has been concluded that experiments favor the assignment (i) over (ii) and (iii). Note that its assignment to an iso-singlet $\{DK\}$ molecule, [11] as an additional possibility, has already been rejected, [12] because it leads to the relation $R(\{DK\}) \gg R(D_{s0}^+(2317))_{\rm exp}$.

From the above considerations, we see that it is natural to assign $D_{s0}^+(2317)$ to $\hat{F}_I^+$. However, its neutral and doubly charged partners, $\hat{F}_I^0$ and $\hat{F}_I^{++}$, have not yet been observed experimentally [13, 14, 15]. With this in mind, in this short note, we study the production of charm-strange scalar four-quark mesons ($\hat{F}_I^{++,+,0}$ and $\hat{F}_0^+$) in relation to the observation of $D_{s0}^+(2317)$ by assigning it to $\hat{F}_I^+$ and discuss why experiments have observed $D_{s0}^+(2317)$ but not its neutral and doubly charged partners. To this end, we consider their production through weak interactions as a possible mechanism, because OZI-rule violating productions of multiple $q\bar{q}$ pairs and their recombinations into four-quark meson states are believed to be strongly suppressed at high energies. (Such multiple $q\bar{q}$ pair creations might produce backgrounds of four-quark meson signals.) First, we construct quark-line diagrams within the minimal (i.e., one) $q\bar{q}$ pair creation, noting the OZI rule. Because there is no diagram yielding $\hat{F}_I^{++}$ production in this approximation, as seen in Fig. 1, it is easy to understand why the BABAR and CLEO experiments did not find any evidence of $\hat{F}_I^{++}$ in $e^+e^- \to c\bar{c}$. Production of iso-triplet $\hat{F}_I^{+,0}$ and iso-singlet $\hat{F}_0^+$ mesons through $e^+e^- \to c\bar{c}$ results from the processes whose diagrams are displayed in Figs. 1(c) and (d). The diagrams Figs. 1(a) and (b) describe productions of $D_s^+\pi^-$, $D_s^{*+}\pi^-$, $D_s^+\rho^-$, etc., and $D_s^+D_s^-$, $D_s^+D_s^{*-}$, $D_s^{*+}D_s^-$, etc. Their weak vertices are given by the color favored spectator diagrams. It is known that such a spectator decay, whose amplitude is proportional to a_1, is much stronger than a color mismatched decay, whose amplitude is proportional to a_2 (explicitly, we have $|a_2/a_1|^2 \simeq 6.8 \times 10^{-3}$ at the scale of the charm mass [16]), as long as non-factorizable contributions are ignored. Here, a_1 and a_2 are the coefficients of the four-quark operators given by products of charged currents and neutral currents, respectively, in the effective weak Hamiltonian after a Fierz reshuffling. In hadronic weak decays of B mesons, non-factorizable contributions are actually small, and they are much smaller at higher energies. Therefore, very large numbers of $D_s^+\pi^-$ events, which are produced through

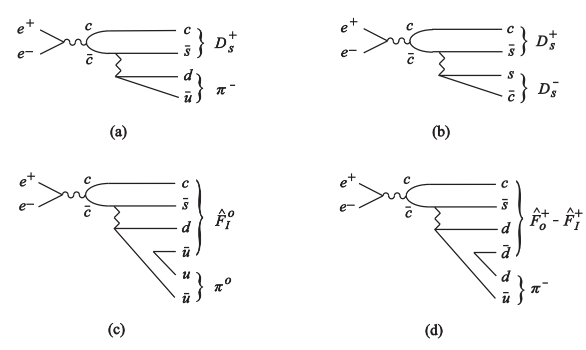

Fig. 1. Production of charm-strange scalar mesons through $e^+e^- \to c\bar{c}$ within the minimal quark-antiquark pair creation. (a) and (b) describe the production of $D_s^+\pi^-$, $D_s^{*+}\pi^-$, $D_s^+\rho^-$, etc. and $D_s^+D_s^-$, $D_s^{*+}D_s^-$, $D_s^+D_s^{*-}$, etc., respectively. The production of $\hat{F}_I^0\pi^0$ and $(\hat{F}_0^+,\, \hat{F}_I^+)\pi^-$ is described by (c) and (d), respectively.

a reaction described by Fig. 1(a) (and semi-inclusive $e^+e^- \to c\bar{c} \to D_s^+\pi^- + X$), would obscure the signal of $\hat{F}_I^0 \to D_s^+\pi^-$ events, which are produced through Fig. 1(c). The latter involves rearrangements of colors, as in color mismatched decays, and is much more strongly suppressed than the color favored ones, as we see in the case of B decays below. For this reason, it is not easy to extract the $\hat{F}_I^0 \to D_s^+\pi^-$ signals in inclusive $e^+e^- \to c\bar{c}$ experiments. Noting these points, it is understood why the CLEO [13] and BABAR [14] experiments found no signal of $\hat{F}_I^0$ and $\hat{F}_I^{++}$. In the case of $\hat{F}_I^+$, however, there do not exist large numbers of background events described by Figs. 1(a) and (b) because its main decay is $\hat{F}_I^+ \to D_s^+\pi^0$. In fact, BABAR [1] and CLEO [2] have observed $D_{s0}^+(2317) \to D_s^+\pi^0$. This seems to imply that the production of four-quark mesons in hadronic weak decays plays an essential role. Figures 1(c) and (d) describe the creation of $\hat{F}_I^0\pi^0$ and $\hat{F}_{I,0}^+\pi^-$, respectively. The iso-triplet $\hat{F}_I^+$ decays dominantly into $D_s^+\pi^0$, but its decay into $D_s^{*+}\gamma$ is strongly suppressed, as discussed above. Therefore, it is easily understood experiments have observed $D_{s0}^+(2317)$ in the $D_s^+\pi^0$ channel but not in the $D_s^{*+}\gamma$ channel. Figure 1(d) includes the production of $\hat{F}_0^+$, which can decay much more strongly into $D_s^{*+}\gamma$ than $D_s^+\pi^0$, as mentioned above. Therefore, it is natural to conjecture that reconstruction of $\hat{F}_0^+ \to D_s^{*+}\gamma$ might be more efficient as a method to search for $\hat{F}_0^+$. However, D_s^{*+} and γ (from $D_s^{*-} \to D_s^-\gamma$) produced in the spectator diagrams Figs. 1(a) and (b) (and in $e^+e^- \to c\bar{c} \to D_s^{*+}D_s^-$, etc., through strong interactions) obscure the above signal of $D_s^{*+}\gamma$. Hence it is clear why experiments have observed no scalar resonance in the $D_s^{*+}\gamma$ channel.

To search for $\hat{F}_I^0$ in $e^+e^- \to c\bar{c}$ experiments, it might be necessary to study an exclusive $e^+e^- \to c\bar{c} \to D_s^+\pi^-\pi^0$ reaction, depicted in Fig. 1(c). Similarly to the situation discussed above, it might be possible to observe $\hat{F}_0^+$ by analyzing an exclusive $e^+e^- \to D_s^{*+}\pi^-\gamma \to D_s^+\pi^-\gamma\gamma$ reaction. To get rid of the large numbers of background events from many other channels, it seems that analyses of exclusive reactions are important; i.e., it would be difficult to pick out the signals of $\hat{F}_I^0 \to D_s^+\pi^-$ and $\hat{F}_0^+ \to D_s^{*+}\gamma$ events if $D_s^+\pi^-$ and $D_s^+\gamma\gamma$ events were collected inclusively.

Because it is difficult to observe $\hat{F}_I^{++}$ in $e^+e^- \to c\bar{c}$ experiments, as discussed above, we now study the production of charm-strange scalar four-quark mesons, $\hat{F}_I^{++,+,0}$ and $\hat{F}_0^+$, in B decays. For this purpose, we again draw quark-line diagrams describing such production within the minimal $q\bar{q}$ pair creation, as above. As expected from Figs. 2 and 3, a resonance peak that is approximately degenerate with $D_{s0}^+(2317)$ has been observed in B decays: $B_u^+ \to \bar{D}^0\tilde{D}_{s0}^+(2317)[D_s^+\pi^0, D_s^{*+}\gamma]$ and $B_d^0 \to D^-\tilde{D}_{s0}^+(2317)[D_s^+\pi^0, D_s^{*+}\gamma]$ in the BELLE experiment [3], and $B_u^+ \to \bar{D}^0(\text{or}\,\bar{D}^{*0})\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$, and $B_d^0 \to D^-(\text{or}\,D^{*-})\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ in the BABAR experiment [4]. Here, the new resonance has been denoted by $\tilde{D}_{s0}^+(2317)$ to distinguish it from the previous $D_{s0}^+(2317)$, although it is usually identified with $D_{s0}^+(2317)$. This is because the BELLE collaboration observed signals that may correspond to the new resonance in both the $D_s^+\pi^0$ and $D_s^{*+}\gamma$ channels. This is quite different from the case in $e^+e^- \to c\bar{c}$ experiments, and therefore it might not be identical to $D_{s0}^+(2317)$, although their masses are approximately equal. The decays mentioned above can proceed through Figs. 2(a) and 3(b), and hence the new resonance can be assigned to $\hat{F}_I^+$ when it is observed in the $D_s^+\pi^0$ channel, while it might be assigned to $\hat{F}_0^+$ when it is observed in the $D_s^{*+}\gamma$ channel,

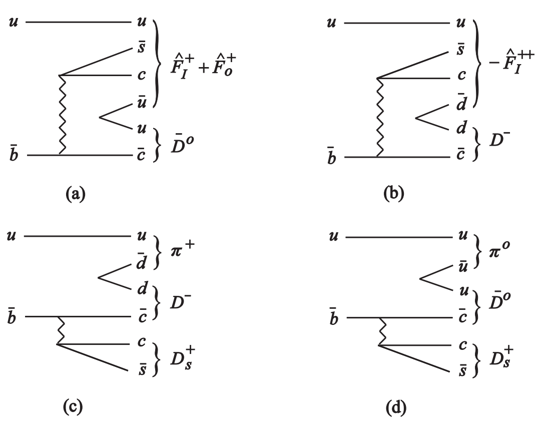

Fig. 2. Production of charm-strange scalar mesons in weak decays of the B_u meson. (a) describes the production of $\hat{F}_I^+$ and $\hat{F}_0^+$ with $\bar{D}^0\,(\text{or}\,\bar{D}^{*0})$, (b) the production of $\hat{F}_I^{++}$ with $D^-\,(\text{or}\,D^{*-})$, and (c) and (d) the production of $D_s^+\pi^+$ with D^- and $D_s^+\pi^0$ with $\bar{D}^0$, respectively.

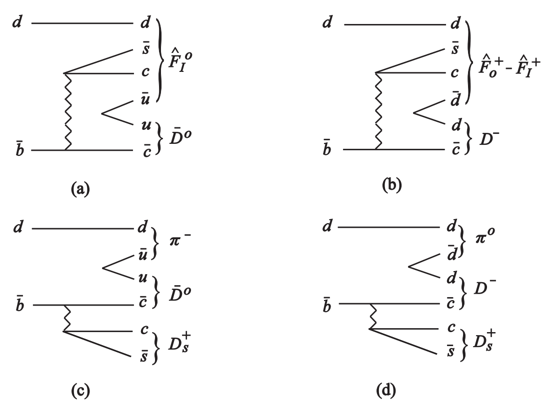

Fig. 3. Production of charm-strange scalar mesons in weak decays of the B_d meson. (a) describes the production of $\hat{F}_I^0$ with $\bar{D}^0$ (or $\bar{D}^{*0}$), (b) the production of $\hat{F}_I^+$ and $\hat{F}_0^+$ with D^- (or D^{*-}). (c) and (d) depict the production of $D_s^+\pi^-$ with $\bar{D}^0$ and $D_s^+\pi^0$ with D^-, respectively.

because these diagrams involve both $\hat{F}_I^+$ and $\hat{F}_0^+$, whose main decays are quite different from each other.

As $\tilde{D}_{s0}^+(2317)$ has been observed in the $B_u^+ \to \bar{D}^0(\mathrm{or}\,\bar{D}^{*0})\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ decay, which is depicted by the diagram in Fig. 2(a), observations of $\hat{F}_I^{++}$ and $\hat{F}_I^0$ are expected in the process $B_u^+ \to D^-(\mathrm{or}\,D^{*-})\hat{F}_I^{++}[D_s^+\pi^+]$, as shown in Fig. 2(b), and in the process $B_d^0 \to \bar{D}^0\hat{F}_I^0[D_s^+\pi^-]$, as shown in Fig. 3(a), respectively. However, amplitudes for the production of $\hat{F}_I^0$ depicted in Figs. 4(a) and (b) interfere destructively, because the anti-symmetry property of the $[cd][\bar{u}\bar{s}]$ wavefunction leads to opposite signs for the $\hat{F}_I^0$ phases in these diagrams. In addition, the spectator decays described by Fig. 4(d) lead to productions of large numbers of background $D_s^+\pi^-$ events. Although the diagrams Figs. 5(a) and (b) also yield the production of $\hat{F}_I^0$ with $\bar{K}^0$, they again interfere destructively, as in the above case.

Because the process $B_u^+ \to D^-\hat{F}_I^{++}$ is depicted by the same type of diagram as $B_u^+ \to \bar{D}^0\hat{F}_I^+$, as seen above, the branching fraction for $\hat{F}_I^{++}$ production can be estimated as

$$\begin{aligned} &B(B_u^+ \to D^-\hat{F}_I^{++}) \\ &\quad\sim B(B_u^+ \to \bar{D}^0\tilde{D}_{s0}^+(2317)[D_s^+\pi^0])_{\mathrm{BABAR}} \\ &\quad\quad = (1.0 \pm 0.3 \pm 0.1^{+0.4}_{-0.2}) \times 10^{-3}. \end{aligned} \tag{2}$$

In addition, the production of $\hat{F}_I^0$ is described by Fig. 3(a). This diagram is of the same type as that in Fig. 3(b), which depicts $B_d \to D^-\hat{F}_I^+$. Hence, the branching fraction for $\hat{F}_I^0$ production can be crudely estimated as

$$\begin{aligned} &B(B_d^0 \to \bar{D}^0\hat{F}_I^0) \\ &\quad\sim B(B_d^0 \to D^-\tilde{D}_{s0}^+(2317)[D_s^+\pi^0])_{\mathrm{BABAR}} \\ &\quad\quad = (1.8 \pm 0.4 \pm 0.3^{+0.6}_{-0.4}) \times 10^{-3}. \end{aligned} \tag{3}$$

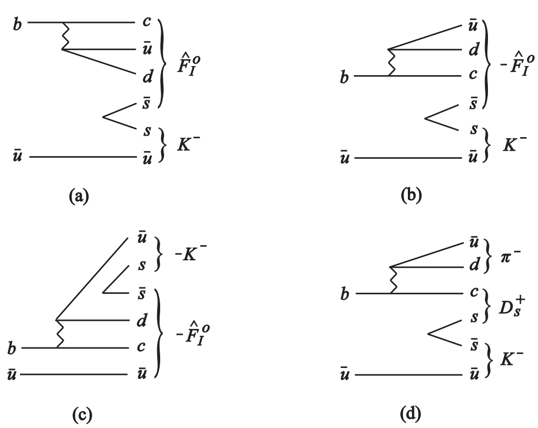

Fig. 4. Production of charm-strange scalar mesons in weak decays of the B_u^- meson. (a), (b) and (c) describe the production of $\hat{F}_I^0$ with K^-, and (d) the production of $D_s^+\pi^-$ with K^-.

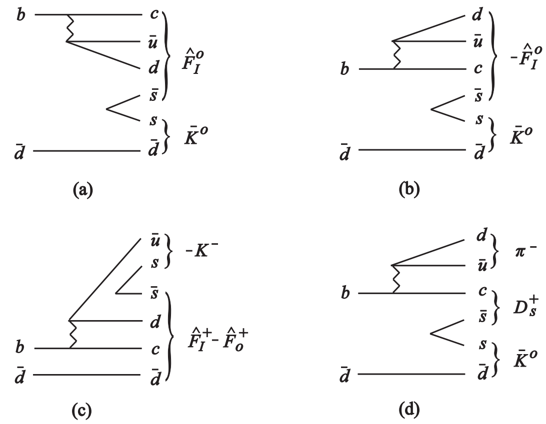

Fig. 5. Production of charm-strange scalar mesons in weak decays of the $\bar{B}_d^0$ meson. (a) and (b) describe the production of $\hat{F}_I^0$ with $\bar{K}^0$, (c) the production of $\hat{F}_I^+$ and $\hat{F}_0^+$ with K^-, and (d) the production of $D_s^+\pi^-$ with $\bar{K}^0$.

In Eqs. (2) and (3), the last equalities were obtained in the BABAR experiment [4].

The BELLE collaboration [17] has observed the $\bar{B}_d^0 \to K^-\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ decay, as depicted in Fig. 5(c), and found

$$\begin{aligned} &B(\bar{B}_d^0 \to K^-\tilde{D}_{s0}^+(2317)) \cdot B(\tilde{D}_{s0}^+(2317) \to D_s^+\pi^0) \\ &\quad = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4) \times 10^{-5}. \end{aligned} \tag{4}$$

Identifying the above $\tilde{D}_{s0}^+(2317)$ with $\hat{F}_I^+$ and taking $B(\tilde{D}_{s0}^+(2317) \to D_s^+\pi^0) \simeq 100$ %, as mentioned above, we obtain the crude estimate

$$B(\bar{B}_d^0 \to K^-\hat{F}_I^+) \sim 10^{-4} - 10^{-5}. \tag{5}$$

This is of the same order as (or slightly smaller than) the measured branching fraction [17] for a typical color mismatched decay, $B(\bar{B}_d^0 \to D^0\pi^0)_{\mathrm{BELLE}} = (2.31 \pm 0.12 \pm 0.23) \times 10^{-4}$. This seems reasonable, because both of these decays involve rearrangements of colors before going to the final states, and because the former includes an $s\bar{s}$ pair creation. Using Eq. (5) as the input data, we now estimate the branching fraction for production of $\hat{F}_I^0$. The $B_u^- \to K^-\hat{F}_I^0$ decay is depicted in Fig. 4(c), which is of the same type as Fig. 5(c) describing the decay $\bar{B}_d^0 \to K^-\hat{F}_I^+$. As $\hat{F}_I^+$ is identified with $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$, it is expected that

$$\begin{aligned} &B(B_u^- \to K^-\hat{F}_I^0) \\ &\quad\sim B(\bar{B}_d^0 \to K^-\hat{F}_I^+) \sim 10^{-4} - 10^{-5}, \end{aligned} \tag{6}$$

if the contributions depicted in Figs. 4(a) and (b) cancel.

Next, we consider the search for the iso-singlet $\hat{F}_0^+$ meson. Although $\hat{F}_I^+$ and $\hat{F}_0^+$ can be produced in B decays described by the same diagrams, $\hat{F}_I^+$ decays dominantly into $D_s^+\pi^0$, but the radiative $D_s^{*+}\gamma$ decay is strongly suppressed, so that the assignment of $D_{s0}^{+}(2317)$ to $\hat{F}_{I}^{+}$ is consistent with Eq. (1). By contrast, in the case of $\hat{F}_{0}^{+}$, its radiative decay is much stronger than the isospin non-conserving $D_s^+\pi^0$ decay; i.e., we have $B(\hat{F}_0^+ \to D_s^{*+}\gamma) \gg B(\hat{F}_0^+ \to D_s^+\pi^0)$. Therefore, if the masses of $\hat{F}_0^+$ and $\hat{F}_I^+$ are approximately equal and they are produced in B decays represented by the same diagrams, Figs. 2(a), 3(b) and 5(c), it should be possible to observe them as resonances with nearly equal masses in the two channels $D_s^+\pi^0$ and $D_s^{*+}\gamma$. In fact, the BELLE experiment [3] has observed an indication of a resonance peak degenerate with $D_{s0}^+(2317)$ in the $D_s^{*+}\gamma$ channel, as well as the $D_s^+\pi^0$ channel.

Although the CDF collaboration also has studied spectra of $D_s^+\pi^\pm$ produced inclusively from the Tevatron, neutral and doubly charged partners of $D_{s0}^+(2317)$ have not been observed. In this case, however, it is believed that very large numbers of background $D_s^+\pi^\pm$ events are produced, because the beam energy is very high. Therefore, it would be very difficult to extract the signal of $\hat{F}_I^0 \to D_s^+\pi^\pm$ events in this kind of experiment.

In summary, we have studied the production of charm-strange scalar four-quark mesons through hadronic weak decay. For this purpose, we have drawn quark-line diagrams within the minimal $q\bar{q}$ pair creation and have found that detecting neutral and doubly charged partners of $D_{s0}^+(2317)$ in inclusive $e^+e^- \to c\bar{c}$ is likely quite difficult, although $D_{s0}^+(2317)$ itself has already been observed. Taking these points into consideration, we have studied the possibility of their detection in hadronic weak decays of B mesons. We have estimated the branching fractions for decays of B mesons producing $\hat{F}_I^{++}$ and $\hat{F}_I^0$ as $B(B_u^+ \to D^-\hat{F}_I^{++}) \sim B(B_d^0 \to \bar{D}^0\hat{F}_I^0) \sim 10^{-3}$ and $B(B_u^- \to K^-\hat{F}_I^0) \sim 10^{-4} - 10^{-5}$. Singly charged $\hat{F}_I^+$ and $\hat{F}_0^+$ are produced in hadronic weak decays of B mesons described by the same diagrams. However, $\hat{F}_I^+$ decays dominantly into $D_s^+\pi^0$, while the $\hat{F}_0^+ \to D_s^+\pi^0$ decay is much weaker than the $\hat{F}_0^+ \to D_s^{*+}\gamma$. Therefore, we conclude that $\hat{F}_I^+$ and $\hat{F}_0^+$ could be observed as resonances with approximately equal masses in two different channels, $D_s^+\pi^0$ and $D_s^{*+}\gamma$, as the BELLE collaboration observed.

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